Preliminary Design and Analysis of an Environmentally Friendly 5.56 mm Bullet to Replace the M855

W. Lawhorn, S. Bless, F. Brody, and R. Kline

Institute for Advanced Technology
The University of Texas at Austin

September 2007

IAT.R 0507

Approved for public release; distribution unlimited.

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
19 OCT 2007	**N/A**	**19 OCT 2006 - 19 Oct 2007**

4. TITLE AND SUBTITLE **Preliminary Design and Analysis of an Environmentally Friendly 5.56 mm Bullet to Replace the M855**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **W. Lawhorn, S. J. Bless, F. Brody, and R. Kline**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER **IAT PO 9463**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Institute for Advanced Technology The University of Texas at Austin 3925 W Braker Lane STE 400 Austin, TX 78759-5316**	8. PERFORMING ORGANIZATION REPORT NUMBER **IAT.R 0507**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **LiquidMetal Technologies Lake Forest, California**	10. SPONSOR/MONITOR'S ACRONYM(S) **LQMT** 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT
The University of Texas at Austins Institute for Advanced Technology (IAT) performed a configuration design and aeroballistic performance characterization study of a 5.56 mm bullet suitable for replacement of the existing M855 ball ammunition, which has a full metal jacket with lead alloy core and a steel penetrator. The scope of the study effort was to evolve a suitable, environmentally friendly replacement round that is compatible with the M249, M16 family, and M4 series weapons. Principal features of the conceptual design are an improved ballistic coefficient and replacement of lead antimony in the bullet core with a LiquidMetal Technologies (LQMT) penetrator core. Aerodynamic characterization via computational fluid dynamics modeling has been accomplished to facilitate flight dynamic simulation. The LQMT high density core easily penetrates steel targets, and the truncated projectile boattail provides less resistance to tumbling in a soft target. The unitary LQMT penetrator profile is scalable to any rifle or machine gun bullet with only minor changes in mass distribution and, hence, flight characteristics. The IAT was assisted in this effort by New Jersey-based consultants Frank Brody and Roy Kline, who provided invaluable consulting expertise in small-caliber projectile design.

15. SUBJECT TERMS
aeroballistic performance characterization study, 5.56 mm bullet, M855 ball ammunition, full metal jacket, lead alloy core, steel penetrator, M249, M16 family, and M4 series weapons

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**20**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Table of Contents

Preliminary Design and Analysis of an Environmentally Friendly 5.56 mm Bullet to Replace the M855

W. Lawhorn, S. Bless, F. Brody, and R. Kline
Institute for Advanced Technology, The University of Texas at Austin

Abstract—The University of Texas at Austin's Institute for Advanced Technology (IAT) performed a configuration design and aeroballistic performance characterization study of a 5.56 mm bullet suitable for replacement of the existing M855 ball ammunition, which has a full metal jacket with lead alloy core and a steel penetrator. The scope of the study effort was to evolve a suitable, environmentally friendly replacement round that is compatible with the M249, M16 family, and M4 series weapons. Principal features of the conceptual design are an improved ballistic coefficient and replacement of lead antimony in the bullet core with a LiquidMetal Technologies (LQMT) penetrator core. Aerodynamic characterization via computational fluid dynamics modeling has been accomplished to facilitate flight dynamic simulation. The LQMT high-density core easily penetrates steel targets, and the truncated projectile boattail provides less resistance to tumbling in a soft target. The unitary LQMT penetrator profile is scalable to any rifle or machine gun bullet with only minor changes in mass distribution and, hence, flight characteristics. The IAT was assisted in this effort by New Jersey-based consultants Frank Brody and Roy Kline, who provided invaluable consulting expertise in small-caliber projectile design.

1 Executive Summary

The University of Texas at Austin's Institute for Advanced Technology (IAT) has performed a brief, top-down design and aeroballistic performance characterization study of the moldline definition and inboard material arrangement of a 5.56 mm bullet suitable for replacement of the existing M855 ball ammunition. The principal features of the conceptual design are an improved ballistic coefficient compared with that of the M855 and replacement of lead antimony in the bullet core with an environmentally friendly LiquidMetal Technologies (LQMT) alloy penetrator core. This design is called the *green bullet*.

The IAT was assisted in this study effort by New Jersey-based consultants Frank Brody and Roy Kline, who provided invaluable expertise in small-caliber projectile design requirement definition, required mass property distribution, and interior/exterior component arrangement and moldline definition.

Study documentation is included herein and contains the following:

- 5.56 mm projectile design requirements and desired performance characteristics.
- Detailed description of the recommended bullet configuration.
- Preliminary aerodynamic force and moment coefficient estimates derived via computational fluid dynamics (CFD) panel code modeling.
- Preliminary estimates of mass properties derived via SolidWorks modeling.

- Exterior ballistic performance estimates derived via six-degrees-of-freedom (6-DOF) simulation.
- Estimated projectile penetration of steel and gelatinous targets at ranges to 300 m or more.
- Preliminary projectile dispersion analysis, exclusive of human factors, using a notional error budget for contributing factors.

2 Background

The M855 ball ammunition round weighs 62 grains and has a full metal jacket with a lead alloy core and a steel penetrator. Figure 1 details pertinent background information about the M855 round. The scope of the present study effort is to evolve a suitable replacement that is compatible with the M249, M16 family, and M4 series weapons.

Figure 1. M855 5.56 mm bullet and cartridge information.

3 Technical Approach

Design requirements and desired operational characteristics for the green bullet are summarized as follows:

1. Accuracy of two minutes of angle (MoA), or 59 mils, at 300 m, ± 0.25 MoA, in production, exclusive of human aiming factors.
2. Penetration of North Atlantic Treaty Organization (NATO) standard steel target 1/8 inch thick at a minimum of 300 m range.
3. Penetration of auto glass at 100 m without deflection.
4. Penetration of 9 inches of ordnance gelatin while achieving maximum yaw and fragmentation at a depth of 4 inches or less.
5. Maximum wound cavity of six to ten inches in length, with a total penetration depth of 12 inches at a range of 50 m.
6. Exploitation of LQMT alloys and manufacturing processes:
   - Tailorable core densities from 7–17 g/cc.
   - Self-sharpening behavior during hard-target penetration.
   - Ease of fragment formation, or core frangibility.
   - Bonding with tungsten and other metallics.
   - Environmentally neutral.
   - Ease of casting and bonding.
7. Projectile resistive to diametric expansion, or mushrooming, in human tissue.
8. All projectile particles visible in x-rays.

4 Conceptual Bullet Configuration

Key configuration figures of merit include reduced drag, adequacy of dynamic stability, and internal component arrangement. Aerodynamic characterization via CFD modeling has been accomplished to facilitate flight dynamic simulation.

The 5.56 mm projectile design, depicted in Figure 2, has a fineness ratio (length to diameter, or L/D) of 4.18, and is spin stabilized. The forebody profile is a secant ogive with a fineness ratio of 2.11 and hemispherical rounding at the tip equal to 23.2 % of the maximum body cross-sectional radius. The midbody cannelure for cartridge case crimping is similar to that of the M855. The truncated boattail has a fineness ratio of 0.73 with a semi-vertex angle of 9.51 degrees.

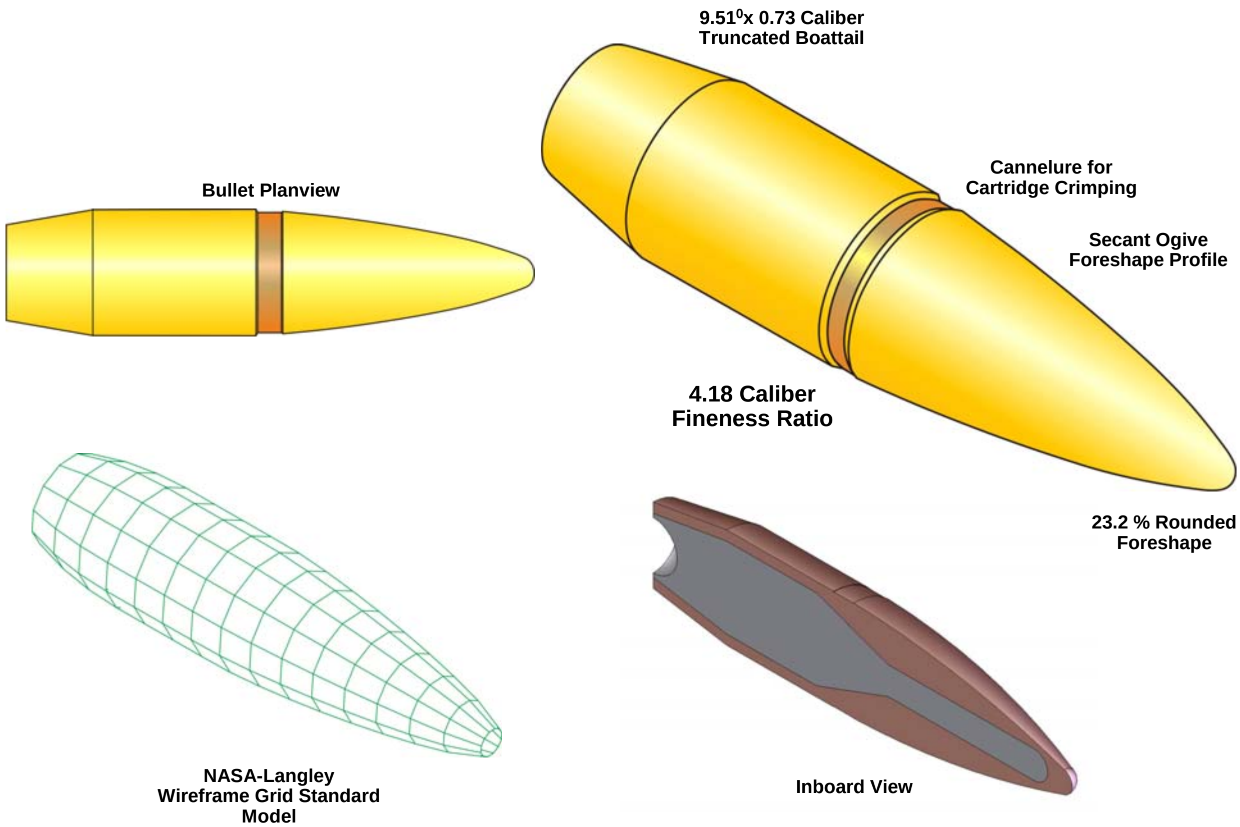

Figure 2. Preliminary 5.56 mm conceptual bullet configuration.

Internal and external configuration details for the green bullet are presented in Figure 3.

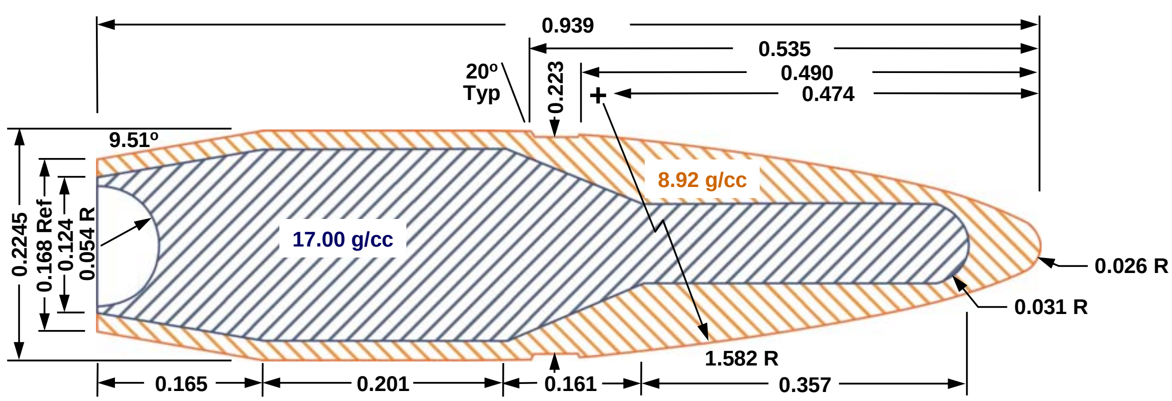

Figure 3. Preliminary 5.56 mm bullet configuration details.

5 Conceptual Bullet Aerodynamic Estimates

Aerodynamic force and moment coefficients, referenced to the bullet maximum cross-sectional diameter, are tabulated as a function of free-stream Mach number in Table 1. Coefficients have been estimated using the National Aeronautics and Space Administration (NASA) Ames potential flow, vortex lattice, paneling code. Viscous effects are superimposed upon the otherwise inviscid panel code results. Damping in pitch (C_{MQ}) and small angle-of-attack Magnus yawing moment ($C_{MP\alpha}$) are referenced to the dimensionless parameters $QD/2V$ and $PD/2V$ respectively, where Q is pitch rate and P roll rate, both in rad/s. In addition, projectile mass and mass moments of inertia have been estimated using SolidWorks. Projectile interior ballistics are beyond the scope of the present effort; therefore, muzzle energy for the M855 (1,334 ft-lb_f) has been used as baseline for the conceptual projectile design. The resulting muzzle velocity reduces to 822 m/s or 2,697 ft/s. Physical parameters are shown in Table 2.

Table 1. Aerodynamic Force and Moment Coefficients

Mach	C_{A0}	$C_{N\alpha}$ **1/rad**	x_{cp} **cal from nose**	$C_{M\alpha}$ **1/rad**	C_{MQ} **1/rad**	C_{lp} **1/rad**	$C_{MP\alpha}$ **1/rad2**
1.5	0.3416	2.222	-1.540	2.245	-4.54	-0.037	-0.239
2.0	0.2895	2.471	-1.637	2.255	-4.12	-0.037	-0.543
2.5	0.2522	2.515	-1.846	1.770	-2.49	-0.036	-0.634
3.0	0.2373	2.375	-1.921	1.494	-1.88	-0.032	-0.680

Table 2. Physical Parameters

D_{ref}	0.2245 inches
Weight	0.0118 lb_m
x_{cg}	0.572 inches
(From Nose)	(2.550 cal)
Length	0.939 inches
I_{xx}	0.0001 lb-in^2
I_{yy}	0.0006 lb-in^2
V_{muz}	2,697 ft/s
P_{muz}	3,596 Hz

Estimated axial force versus Mach number is depicted in Figure 4 for the M855 and conceptual green bullet configurations. M855 data are taken from the Armament Research, Development and Engineering Center (ARDEC) aeroballistic model. Drag reduction for the green bullet is achieved through a combination of increased forebody fineness ratio and longer boattailing to reduce base drag.

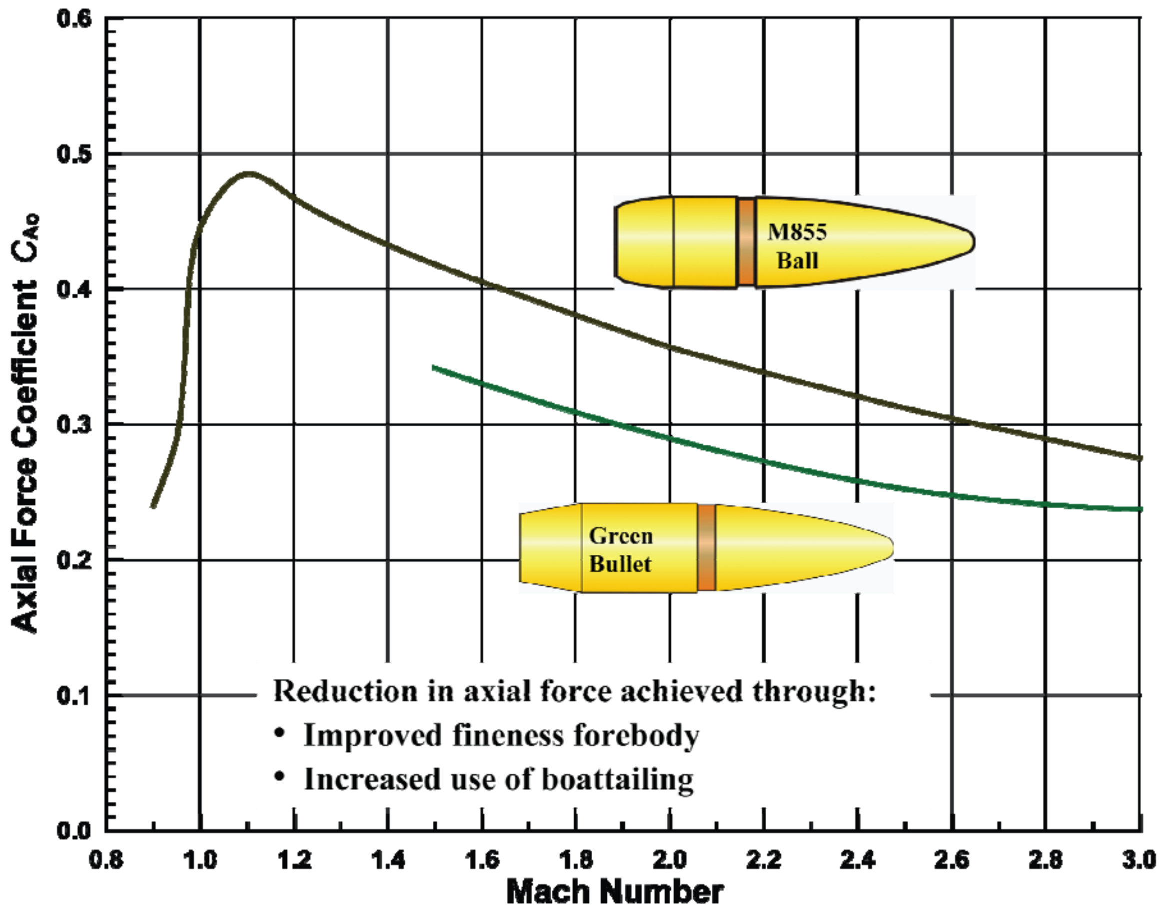

Figure 4. Estimated projectile axial force coefficient.

Figures 5 and 6 contain estimated normal force coefficients and axial center of pressure locations for the M855 and the conceptual green bullet design. Center of pressure relative to center of mass is critical in determining spin-stabilized bullet overturning moment in free flight. The conceptual green bullet design compares favorably with the M855 in that regard.

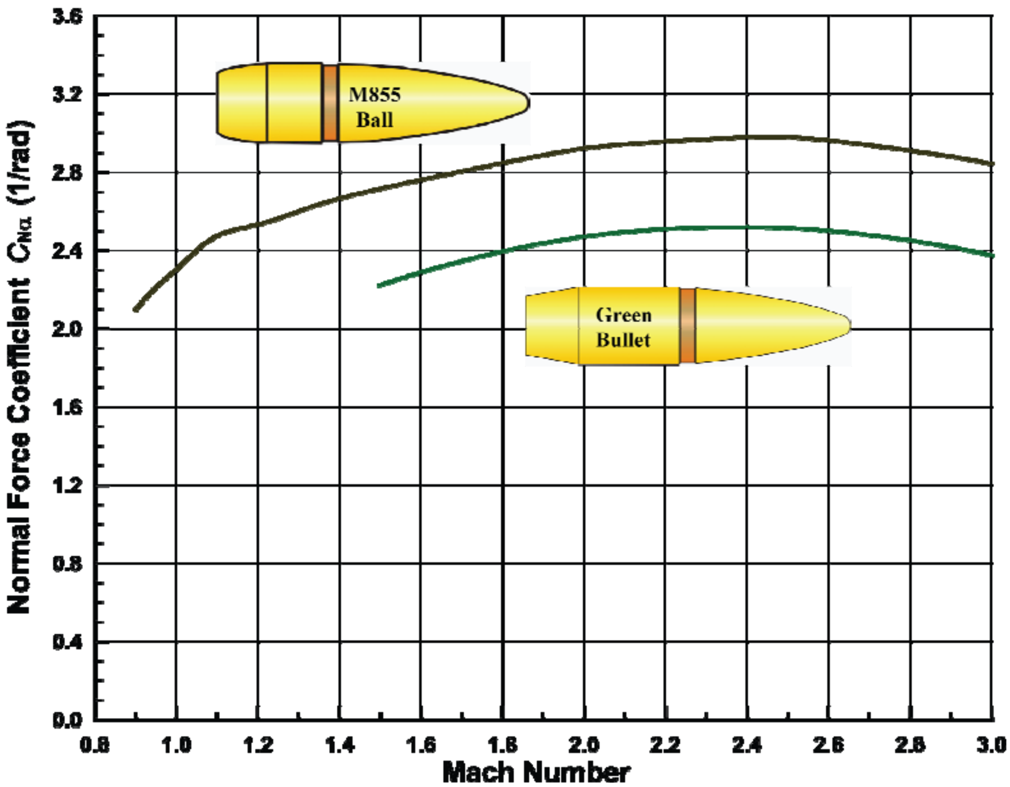

Figure 5. Estimated projectile normal force coefficient.

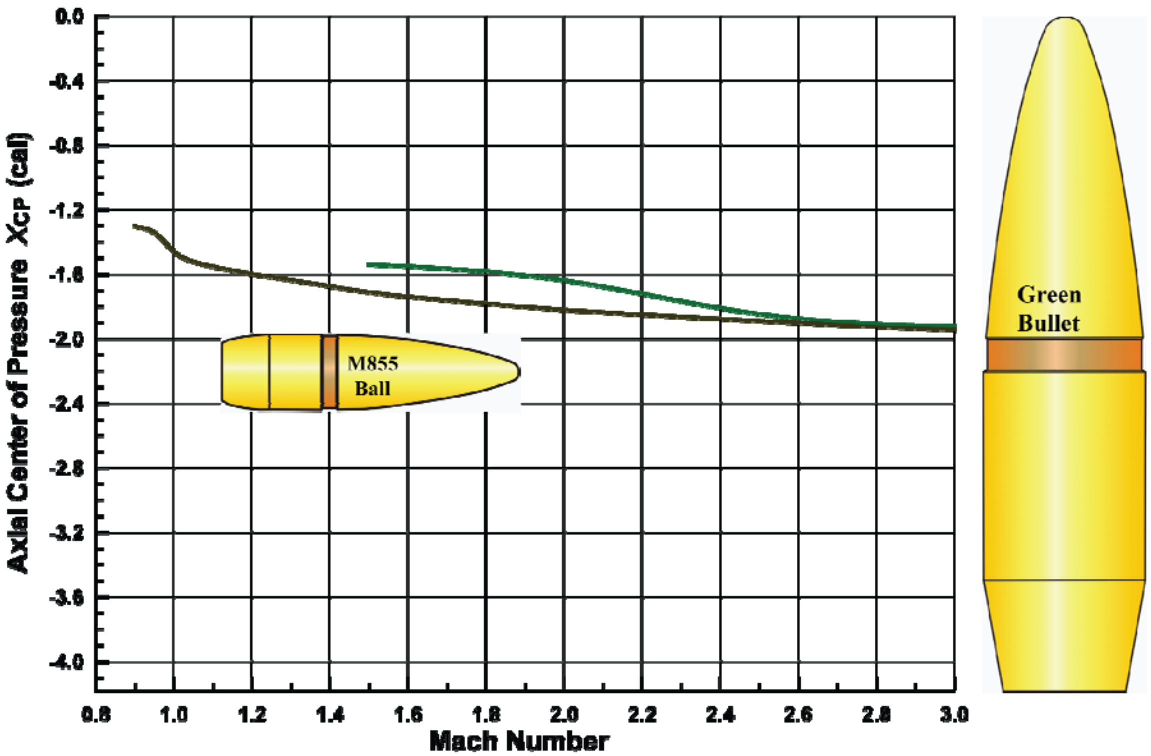

Figure 6. Estimated projectile axial center of pressure location from the nose.

6 Aeroballistic Performance Estimates

Figure 7 compares estimated exterior ballistics of the conceptual green bullet with those of the M855. Sources for these data are the M855 database and the 6-DOF simulation of the conceptual projectile. The conceptual green bullet has a lower muzzle velocity due to the 20.6-grain weight differential between the two configurations. However, the conceptual green bullet overtakes the M855 in velocity at a range of ~ 300 m owing to the higher ballistic coefficient (weight/[cross-sectional area × drag]). This results in a kinetic energy advantage for the conceptual green bullet.

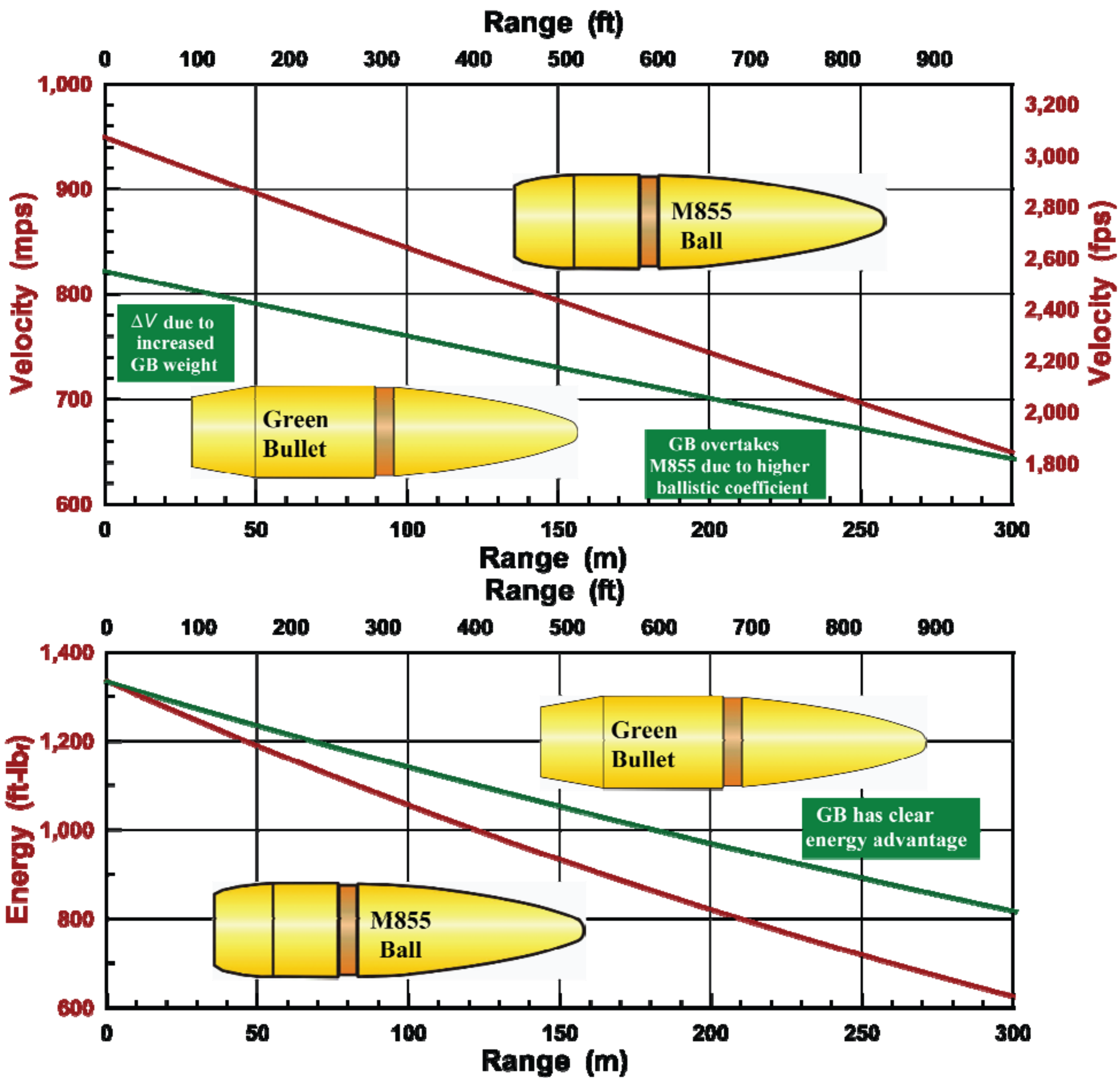

Figure 7. Exterior ballistic estimates for the M855 and conceptual green projectiles.

Figure 8 is a classical-looking epicyclic modal analysis in pitch and yaw angles of attack resulting from first maximum yaw rate (35 rad/s simulated) at the muzzle. The source of these data is 6-DOF simulation. Note that the fast-arm, or *nutation*, frequency is high due to the very high projectile roll rate, while damping is low. The slow-arm, or *precession*, frequency is lower and appears to exhibit little, if any, damping. The foregoing is characteristic of most spin-stabilized projectiles. At transonic speeds, epicyclic motion will likely become undamped, resulting in slowly growing angles of attack, or *coning*, leading ultimately to keyholing, or *catastrophic yaw*.

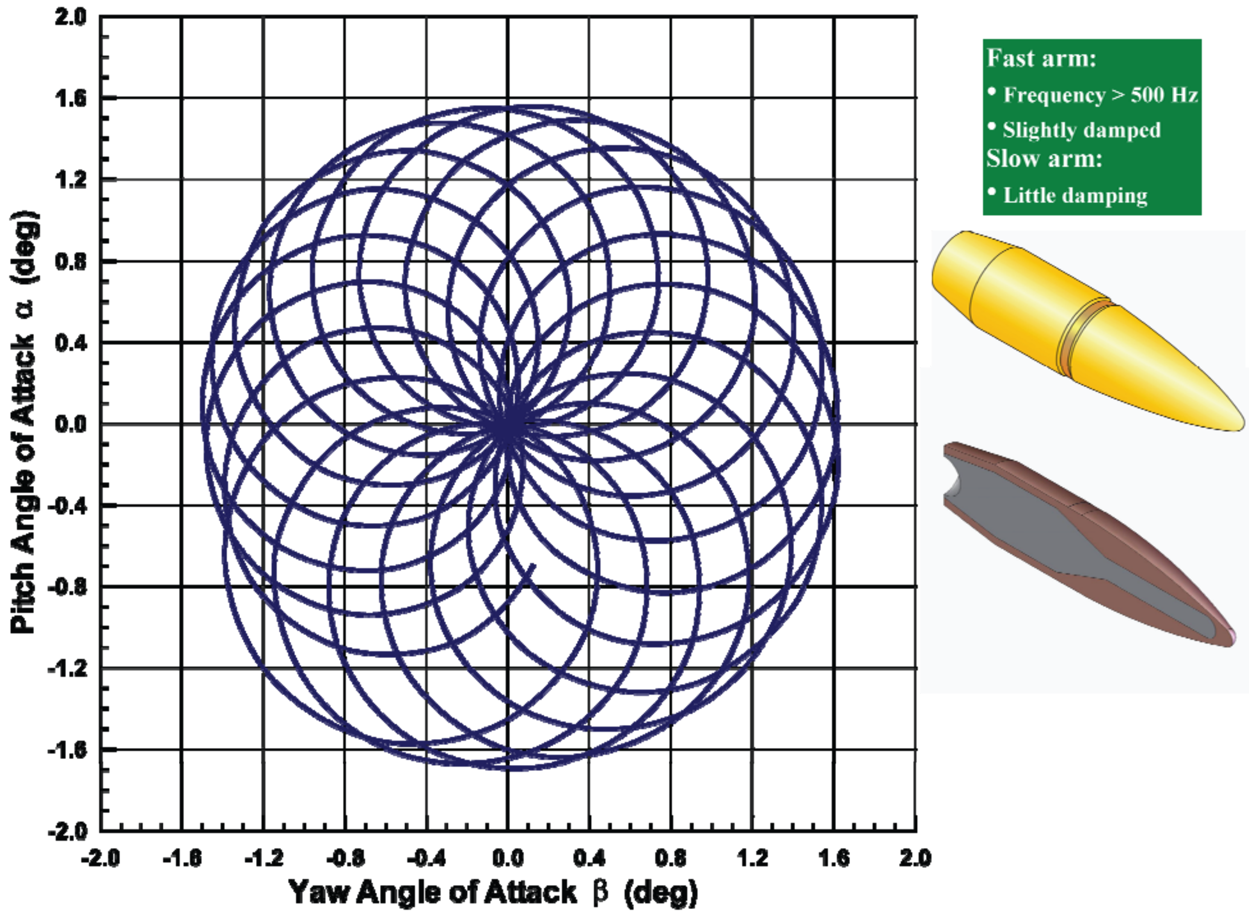

Figure 8. Estimated projectile epicyclic modal behavior.

7 Preliminary Dispersion Estimates

Excluding human aiming factors, a dispersion analysis (Table 3) was performed using the notional error budget presented. Projectile weight, mass properties, drag, muzzle jump, and wind were varied stochastically. Error budget values represent the assumed one-standard-deviation amounts about the mean for each component. There are other variables comprising a more thorough error budget, but that is beyond the scope of the present effort.

Results suggest a fairly low dispersion circular error probable (CEP) of about 1.44 minutes of angle at 300 m range, with a high probability of hitting a facing man-sized target.

Table 3. Dispersion Analysis of Conceptual Green Bullet, Ground Range = 307.10 m

<table>
<tr><th colspan="7">Initial Conditions</th></tr>
<tr><td colspan="2">Gun elevation = 1.78 mils</td><td colspan="3">Altitude = 0.46 m</td><td colspan="2">Downwash = 0.00 m/s</td></tr>
<tr><td colspan="2">Gamma = 1.78 mils</td><td colspan="3">Weight = 82.60 grains</td><td colspan="2">Pitch rate = 0.00 rad/s</td></tr>
<tr><td colspan="2">Velocity = 822 m/s</td><td colspan="3">Wind direction = 45.00 degrees</td><td colspan="2">Wind speed = 5.00 knots</td></tr>
<tr><th colspan="7">Nominal Trajectory</th></tr>
<tr><td colspan="7">Angle of fall = -0.30 degrees</td></tr>
<tr><td colspan="7">Cross-range bias = -0.21 m</td></tr>
<tr><td colspan="7">Bias deflection = -0.69 m-rad</td></tr>
<tr><th colspan="7">Plane Normal to Flight Path</th></tr>
<tr><th>Error Component</th><th>Standard Deviation</th><th>Cross Range (m)</th><th>Down Range (m)</th><th>Angle of Fall</th><th>Cross Range Error Cmp</th><th>Down Range Error Cmp</th></tr>
<tr><td>Weight variation (g)</td><td>1.65</td><td>0.003</td><td>0.027</td><td>-0.29</td><td>0.002 m/g</td><td>0.022 m/g</td></tr>
<tr><td>CG offset (mm)</td><td>0.47</td><td>0.006</td><td>0.009</td><td>-0.29</td><td>0.013 m/mm</td><td>0.020 m/mm</td></tr>
<tr><td>Drag variation (%)</td><td>2.00</td><td>0.003</td><td>0.003</td><td>-0.28</td><td>0.000 m/%</td><td>0.003 m/%</td></tr>
<tr><td>Muzzle jump variation (dps)</td><td>1012.86</td><td>0.003</td><td>0.107</td><td>-0.29</td><td>0.000 m/dps</td><td>0.000 ft/dps</td></tr>
<tr><td>Wind variation (%)</td><td>100.00</td><td>0.104</td><td>0.030</td><td>-0.30</td><td>0.000 m/%</td><td>0.000 m/%</td></tr>
<tr><th colspan="7">Total cross range = 0.34 m-rad, DEP = 0.23 m-rad</th></tr>
<tr><th colspan="7">Total down range = 0.37 m-rad, REP = 0.25 m-rad</th></tr>
<tr><th colspan="7">System total = 0.36 m-rad</th></tr>
<tr><th colspan="7">CEP = 0.42 m-rad (1.44 MoA)</th></tr>
<tr><th colspan="7">Hit probability = 0.98 (1 m-rad target, or target 1.96 ft across</th></tr>
</table>

8 Estimated Target Penetration Characteristics

Using sheet 4340 steel as the assumed target medium, AUTODYN-2D target penetration stages are illustrated in Figure 9 from impact through target exit. Surviving projectile fragments are as shown in the figure. Target impact statistics are given in Figure 10 for incident and exit velocities as a function of range, with simulated target thicknesses versus range as shown. Zero obliquity at target impact has been assumed. Average ΔV, or loss of velocity in the target, is around 125 m/s except at short range, where velocity loss is greater.

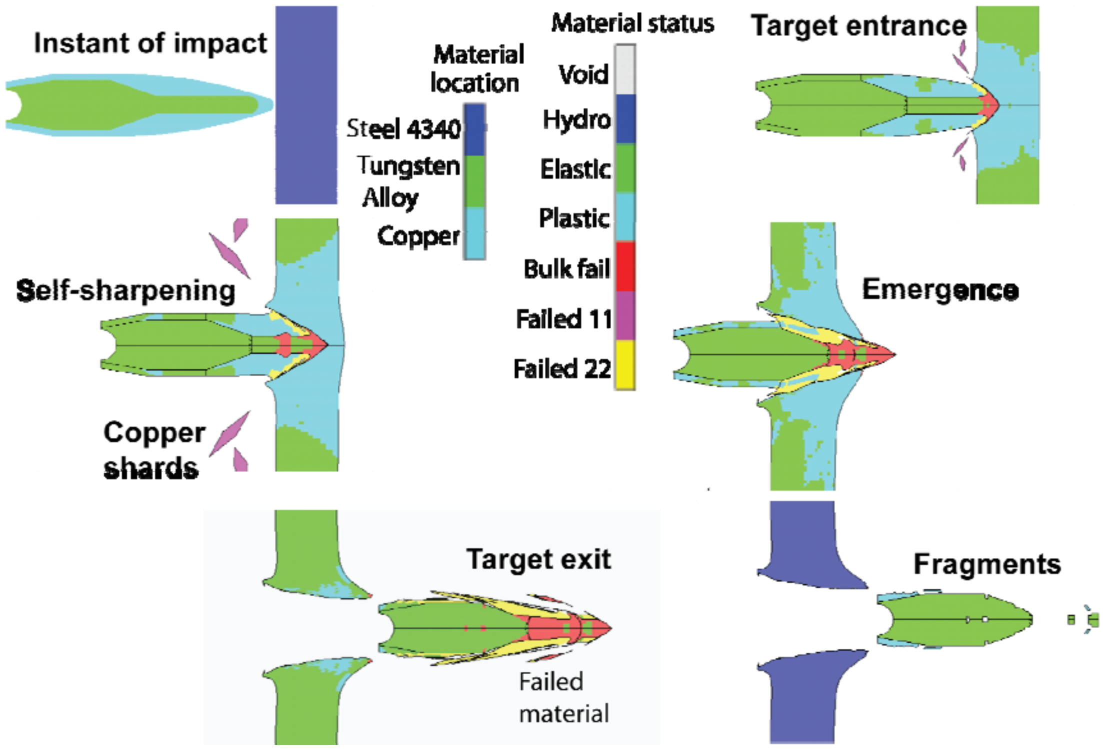

Figure 9. AUTODYN-2D target penetration modeling.

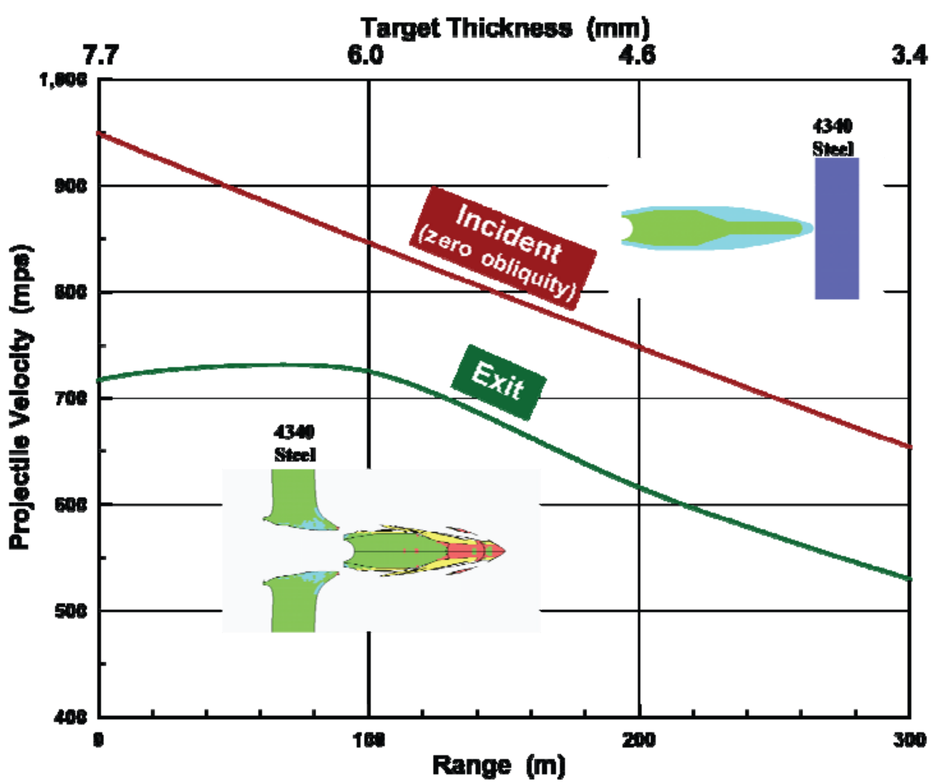

Figure 10. AUTODYN-2D target penetration statistics.

Finally, penetration of ballistic gelatin was simulated to gauge depth of penetration and likely projectile tumbling characteristics. Secondary effects, such as cavitation in the target medium, are beyond the scope of the present effort. Ballistic gelatin has a density of 0.031 lb_m/in^3, or 1.665 $slugs/ft^3$. This is equal to 700 times the density of air at sea level. Figure 11 shows approximate projectile keyhole depth versus incident velocity, and range. *Keyhole depth* is defined as that length of travel within the target at which the projectile tumbles sideways at 90^o to the incoming flight path. The imprint of the projectile at that point resembles a keyhole in appearance. Little forward motion continues after keyholing occurs.

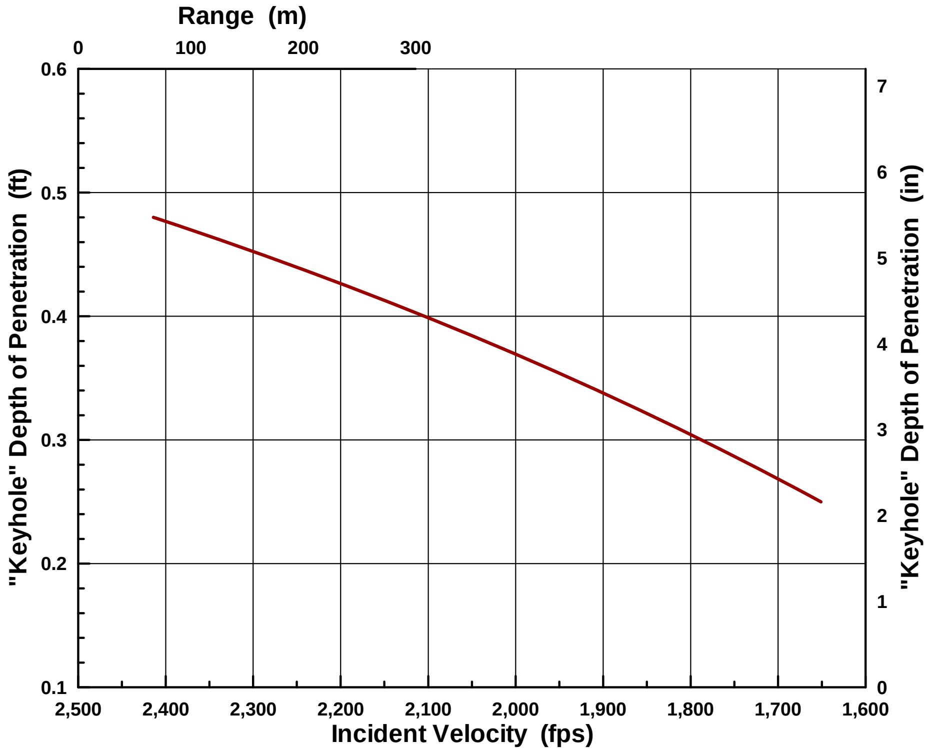

Figure 11. Simulated ballistic gelatin target impact.

9 Multipurpose Attributes and Advantages

The LQMT high-density core easily penetrates steel targets, as will be shown in this report. The rotational, or polar, inertia of the aft section LQMT core helps to provide gyroscopic bullet stability. The thin-walled copper metal jacket near the tip of the penetrator will tend to fracture, sending fragments into the target at impact. The rear cavity allows for a few more grains of propellant while resulting in a slightly more forward center of gravity that further increases gyroscopic stability. The long boattail lowers aerodynamic drag while providing less resistance to tumbling in a soft target.

A two-component bullet (LQMT core in a copper jacket) is less likely to be statically or dynamically unbalanced than a three-component bullet. Static and/or dynamic imbalance results in throwoff at the muzzle with accompanying aerodynamic jump. These are the largest contributors to dispersion. A heavier bullet will likely be more effective at target incapacitation. Kokinakis and Sperrazza [1] recommend $(\text{mass} \times V)^{3/2}$ as a qualitative measure of lethality. The

small angle-of-attack limit cycle in which the projectile will likely fly should start the bullet tumbling quickly in a soft target.

The unitary LQMT mass/forward penetrator profile should be scaleable to any rifle or machine gun bullet with minor changes in mass distribution and, hence, flight characteristics. See Appendix A for two alternative design configurations.

Acknowledgment

The research reported in this document was performed in connection with IAT purchase order 9463 with LiquidMetal Technologies of Lake Forest, California. The views and conclusions contained in this document are those of the authors and should not be interpreted as presenting the policies or position, either expressed or implied, of the sponsoring organization unless so designated by other authorized documents. Citation of manufacturers or trade names does not constitute an official endorsement or approval of the use thereof.

References

1. W. Kokinakis and J. Sperrazza, "Criteria for Incapacitating Soldiers with Fragments and Flechettes," US Army Ballistic Research Laboratory, APG, Md January 1965.

Appendix A

Alternate Bullet Configurations

Alternate bullet configuration Designs 1 and 2, shown in Figures A-1 and A-2, are the same in exterior moldline as that of Figure 3 in the report, with the exceptions of an ellipsoidal base cavity for Design 1 and the somewhat sharper nose of Design 2. The purpose of the larger base cavity is to move the center of mass forward slightly, reduce the transverse moment of inertia and total weight, and, perhaps, accommodate a few more grains of propellant. The aerodynamics of Design 1 should be the same as the configuration of Figure 3 [a]. The fast arm (nutation) mode of Designs 1 and 2 should be damped at all angles of attack. The slow arm (precession) mode will damp to small angles of attack supersonically (~ 2 deg) where limit cycling should occur due to the nonlinearity of the Magnus yawing moment with angle of attack. Thus, Designs 1 and 2 would likely fly in a 0.5 to 2.0 degree angle of attack limit cycle at supersonic velocities, as does the M855. At very long ranges (> 800 m and subsonic velocities), a 3 to 5 degree limit cycle would be expected. Both Designs 1 and 2 should have adequate static stability (launch gyroscopic stability parameter S_g approximately 2) and reasonably good dynamic stability.

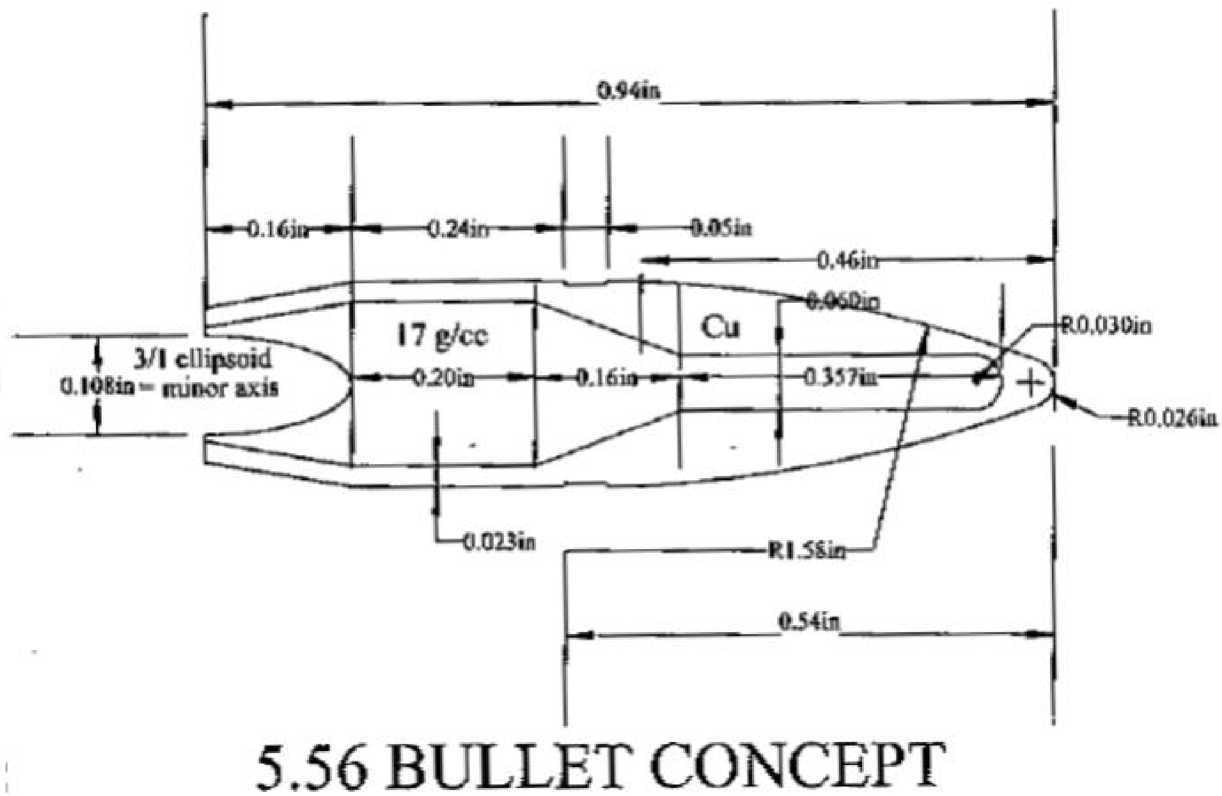

Figure A-1. Alternate Design 1.

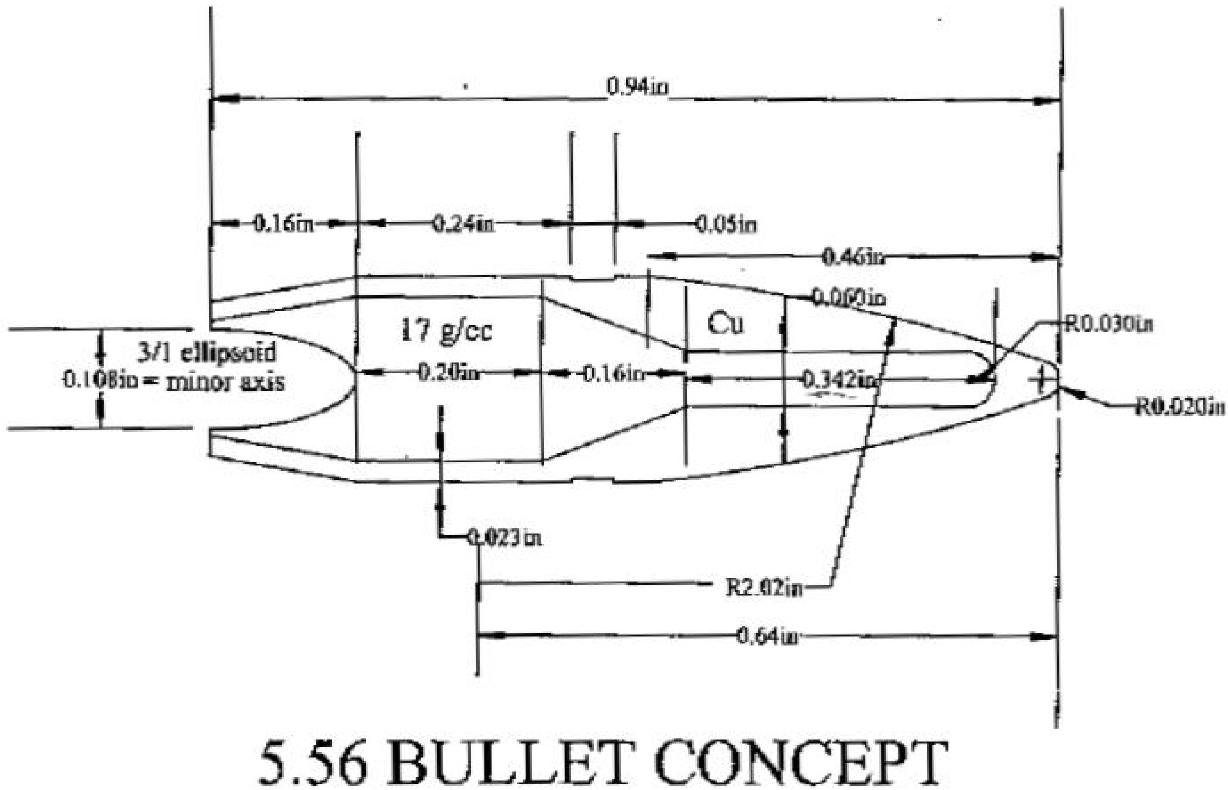

Figure A-2. Alternate Design 2.

Dispersion

In the October 1998 issue of *Precision Shooting* magazine, Harold Vaughn (retired Sandia National Laboratories ballistics expert) estimates that the round-to-round bullet center of gravity offset averages 0.0002 inches in a commercial 270-caliber bullet. McCoy [b] has an equation for throwoff at the muzzle on page 255. Using a simplified jump equation [c] with a muzzle pitch rate of 35 radians per second gives an error of 0.0618 m at 300 m range. This compares reasonably well with a 6-DOF result of 0.0575 m. The classical crosswind deflection formula, $Y = Vx{*}(t - (X/V_0))$, where Vx is the crosswind velocity, t is the time of flight, V_0 is muzzle velocity, and X is range, gives a deflection of 0.182 m for a 10 fps crosswind. The 6-DOF result is 0.178 m. The 6-DOF vertical windage jump of 0.004 m is negligible.

Angular Motion

Figures A-3 through A-6 are charts showing alternative predicted angular motion of the Figure 3 configuration (flight performance of Design 1 would be similar) Figures A-3 and A-4 are simulations of the total angle of attack and the epicyclic motion of Figure 3, assuming no launch disturbance. No significant fast-arm mode is evident, only the slow growth to a 2-degree angle of attack limit cycle. Figures A-5 and A-6 show the total angle of attack and the epicyclic motion of Figure 3 given an initial pitch rate of 35 radians per second. The latter two charts indicate that the fast mode damps quickly, while the slow mode settles into a 2-degree angle-of-attack limit cycle.

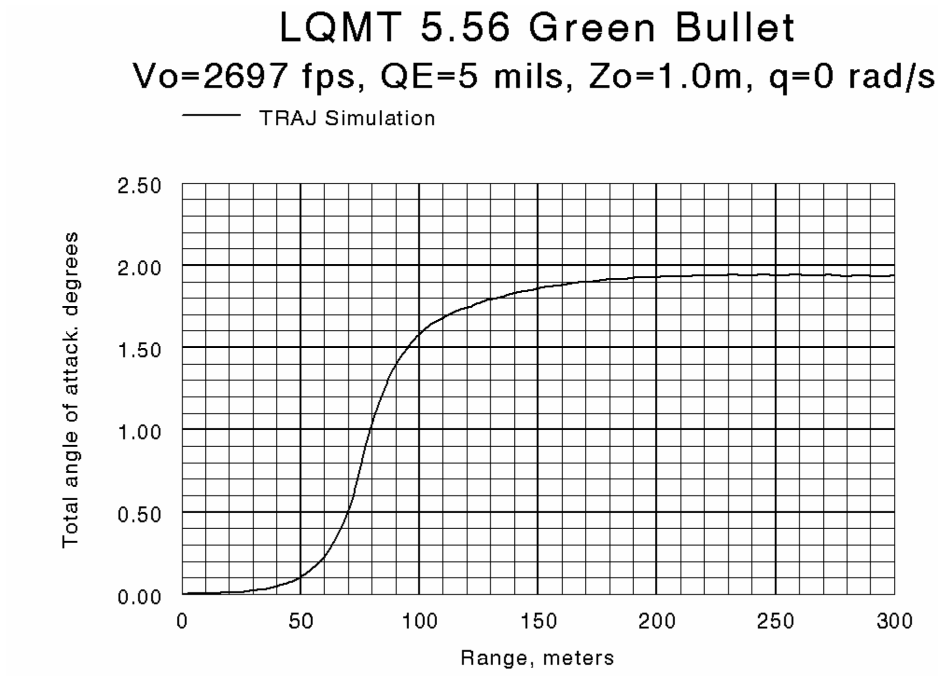

Figure A-3. Total angle-of-attack history absent initial launch disturbance.

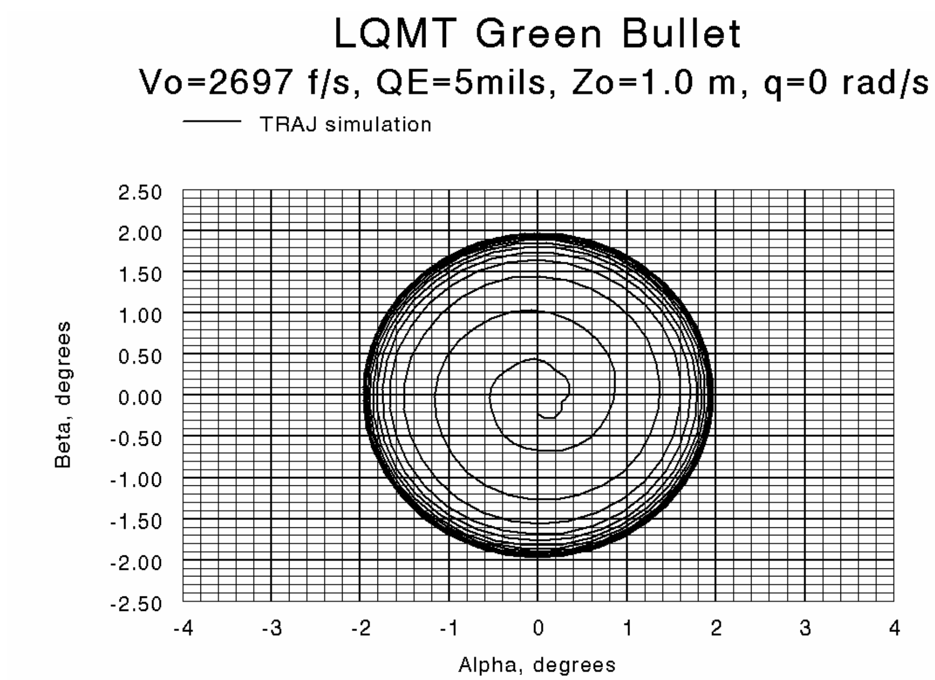

Figure A-4. Epicyclic dynamic motion absent initial launch disturbance.

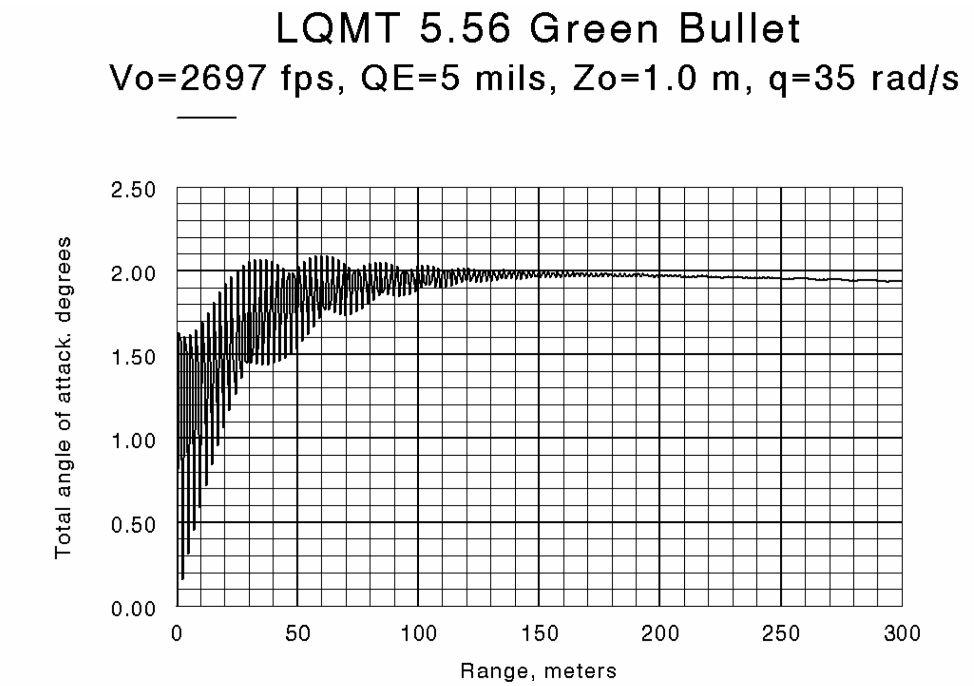

Figure A-5. Total angle-of-attack history with a 35 rad/s launch disturbance.

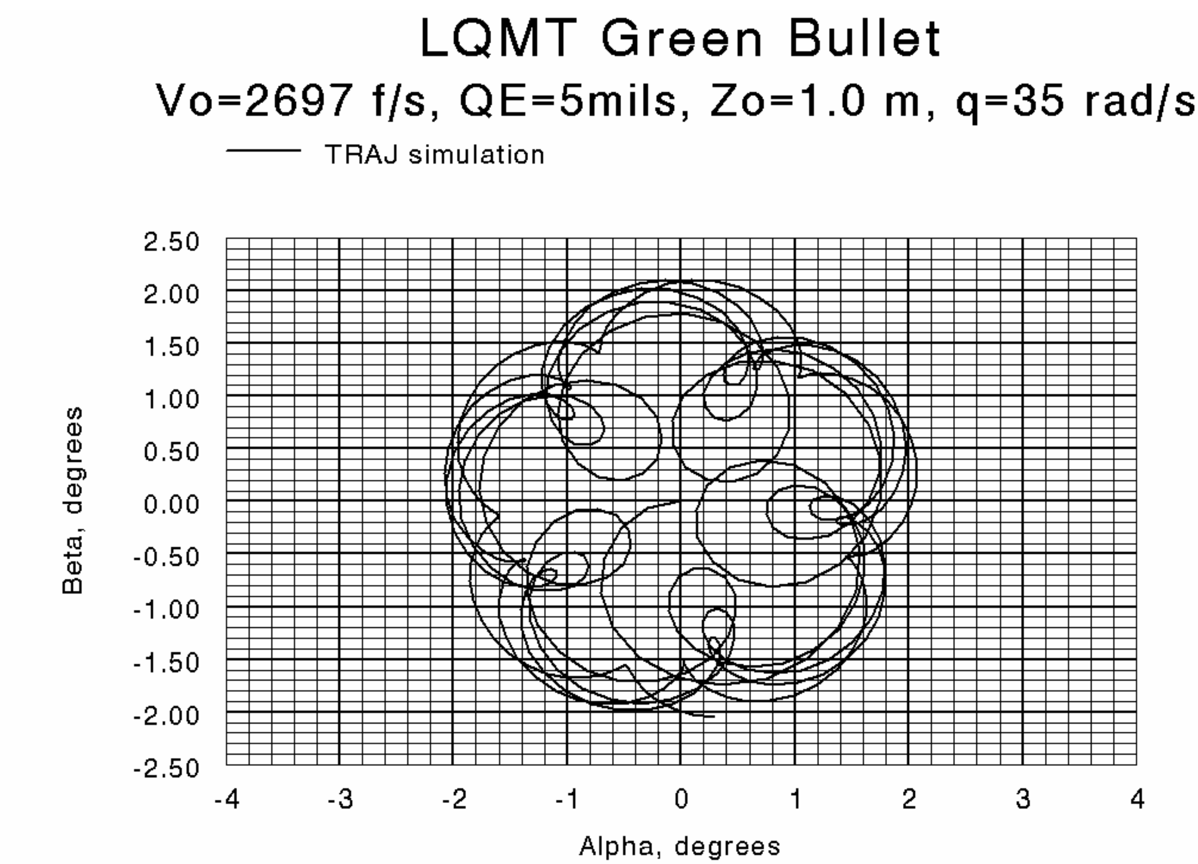

Figure A-6. Epicyclic dynamic motion with a 35 rad/s launch disturbance.

References to Appendix A

a. V. Oskay, "Base Cavity Effects of the Flight Performance of the XM898 SADARM Projectile," Ballistic Research Laboratories Report IMR-963, APG, MD, April 1991.

b. R. McCoy, *Modern Exterior Ballistics,* Shiffer, 1998.

c. J. Nicolaides, *Free Flight Missile Dynamics*, University of Notre Dame, 1968.